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Neutron time-of-flight and emission time diagnostics for the National Ignition Facility

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Abstract

Current plans call for a system of current mode neutron detectors for the National Ignition Facility for extending the range of neutron yields below that of the neutron activation system, for ion-temperature measurements over a wide yield range, and for determining the average neutron emission time. The system will need to operate over a yield range of 10^6 for the lowest-yield experiments to 10^{19} for high-yield ignited targets. The requirements will be satisfied using several detectors located at different distances from the target. This paper presents a conceptual design for the NIF nToF system.

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I. INTRODUCTION

The National Ignition Facility [1] (NIF) is a 2-MJ, 192-beam laser system currently under construction at Lawrence Livermore National Laboratory. One of the main missions of the facility is to achieve thermonuclear ignition of fusion fuel using the indirect drive approach of inertial confinement fusion (ICF). [2]

ICF experiments on NIF will produce neutrons primarily in two reactions:

$$D + D \rightarrow n + {}^{3}\mathrm{He} \tag{1.1}$$

$$D + T \rightarrow n + \alpha \tag{1.2}$$

Neutrons from the upper reaction are referred to as DD neutrons and have average energies of 2.45 MeV. Neutrons from the lower reaction are referred to as DT neutrons and have average energies of 14 MeV.

A set of diagnostics, required to accomplish the various NIF missions, has been identified [3–5]. This set includes a neutron time-of-flight system for measuring ion temperature and average time of neutron emission relative to a fixed point on the laser pulse shape. A system designed to accomplish these tasks can also be used to extend the yield measurement capability below that of activation systems [6,7] and measure secondary neutron yield production when it exceeds the range of a neutron spectrometer designed for that purpose [8,9].

The conceptual design of the system consists of current-mode detectors utilizing plastic scintillators coupled to fast photomultiplier tubes (Fig. 1) and utilizing high-bandwidth transient digitizers to record the signal. Such systems have been used to measure the neutron yield [10], ion temperature [11–15], and neutron emission time [16] of ICF targets on Nova, Omega, and other large ICF facilities. These systems are relatively inexpensive, have large dynamic range, and have fast time response, making them ideal candidates for a reliable base system of diagnostics.

II. CONCEPTUAL DESIGN

The neutron time-of-flight and emission time system is required to fulfill certain requirements as part of the core set of diagnostics for the NIF.

Neutron yields need to be measured from about 1×10^6 DD neutrons, to maintain capabilities that were available on Nova and are currently available on Omega, and going up to high yield ignited targets which would produce up to 1×10^{19} DT neutrons.

Ion temperature measurements are required for yields exceeding approximately 10^7 neutrons. For low yield experiments, ion temperature can be supplied by a multi-hit neutron spectrometer [8,9], but above about 5×10^9, this system saturates, and a current mode system can fill in.

Emission time measurements are needed for experiments that produce on the order of 10^8 neutrons. Accuracies of 100 ps are required for experiments with laser pulse lengths of up to 20 ns.

The requirements for the neutron time-of-flight and emission time system can be met using a system that consists of four detectors (Table I). The detectors consist of plastic scintillators coupled to photomultiplier tubes (Fig. 1), but the size of the scintillator, the distance from target chamber center (TCC), and the type of photomultiplier tube affects the capabilities of each detector in the system. Photomultiplier tubes will be biased with high voltage supplies that are computer controlled. Each detector will be supplied with an optical fiducial pulse which allows operational checks of the system as well as timing verification prior to the shot. A programmable optical attenuator will be used to match the fiducial pulse amplitude to the anticipated neutron signal.

Plastic scintillator is chosen because of its high efficiency for detecting fast neutrons and its fast time response. Previous detectors of this type [10–16] have utilized Bicron BC-422 scintillator (or similar material), or its quenched version which incorporates up to 2% benzephenone to reduce its decay time. The scintillation light from BC-422 has a rise time [17] of less than 20 ps, followed by an exponential decay with a 2-ns decay rate. The quenched version falls with a two component decay with time constants of about 0.6 and 5 ns.

Microchannelplate photomultiplier tubes (MCP-PMTs) are commercially available with time responses on the order of a few hundred ps FWHM and electron gains of order 10^6. Photocathodes on these tubes tend to be smaller than are available on standard photomultiplier tubes, requiring the use of small scintillators or light guides to transition from larger scintillators to smaller photocathodes.

Commercial digital oscilloscopes are now available with 1 GHz bandwidth and 5 gigasample per second digitizing rate. One model, with 15,000 points, allows 3 μs of data to be recorded per channel at the maximum digitizing rate, enough time that x rays, DT neutrons, and DD neutrons can be recorded on a single trace even at the NIF target bay wall.

An optical fiducial signal will allow operation and timing of the instrument to be verified prior to a shot and, for emission time measurements, will allow the timing of the neutron signal to be related back to the laser pulse. The fiducial signal will be attenuated to be the same amplitude as the expected neutron signal. Programmable fiber optic attenuators currently on the market are designed for use at optical communications wavelengths of 1200–1650 nm. Since the NIF fiducial will probably be at doubled Nd:YAG frequency, it will have a wavelength of about 531 nm. Optical attenuators will need to be developed or identified to operate at this wavelength, preferably under computer control.

Each system will be under the control of a front end processor (FEP) computer that will accept commands from the NIF control systems and configure the diagnostic system for a shot. Subsequent to the shot, the FEP will acquire data from the digitizer and send it to the NIF data archiving system.

Two detectors will consist of 5-cm diameter scintillators 0.5-cm thick coupled to an MCP-PMT with a tapered light guide. The detectors will be located at 6 meters and 17 meters from TCC. The 6-meter detector (nToF-6) will be used to measure ion temperatures from DD implosions, and the 17-meter (nToF-17) detector will be used for DT implosions.

The third detector will consist of a 40-cm diameter 5-cm thick scintillator, with a 13 cm diameter hole through the center. This Large Area Neutron Detector (nToF-LAND) will be located at the same location as nToF-6, and the hole through the center will afford a line-of-site for nToF-6. This detector will be coupled to six 5-inch diameter photomultiplier tubes. This detector will be used to measure neutron yields below those measurable by the activation system. [6,7]

The fourth detector will be used to measure the emission time of neutrons from the target. It will consist of a 2.5-cm diameter scintillator 0.5 cm thick, coupled to a MCP-PMT with a tapered light guide. This detector (nToF-ET) will be placed, either by a mechanical system or by placement in a diagnostic instrument manipulator (DIM), formerly called the Twelve Inch Manipulator (TIM) in some references [3], so that the scintillator is approximately 50 cm from TCC. This distance must be kept small so that the time of flight spreading of the neutron signal remains as small as possible, allowing accurate determination of the timing.

III. PERFORMANCE EVALUATION

A. Yield measurements

Neutron yields can be obtained from signals from current-mode neutron detectors. Using the energy dependence of the number of photons created in a typical organic scintillator found by Verbinski [18] and the light output of the proposed scintillator material, typical values for the quantum efficiency of a photocathode, and reasonable values for coupling efficiency of scintillator light to the photocathode, one finds that the number of photons per neutron interacting in the scintillator is high enough that this does not dominate the statistics of the measurement.

The statistics of yield measurements are determined primarily by the number of neutrons interacting in the scintillator. The scattering cross section for neutrons on protons is about 2.6 b at 2.45 MeV, and about 0.6 b at 14 MeV. Using a proton density of 5.2×10^{22} cm^{-3} for the scintillator, one finds that the efficiency ϵ of detecting neutrons for a detector of volume V at distance R from the target can be approximated by:

$$\epsilon = \left\{ \begin{array}{l} 0.011\ \mathrm{cm}^{-1} \\ \\ 0.0025\ \mathrm{cm}^{-1} \end{array} \right\} \frac{V}{R^2} \left\{ \begin{array}{l} DD \\ \\ DT \end{array} \right. \tag{3.1}$$

Ignoring the fact that the thickness of nToF-LAND is approximately equal to the mean free path of 2.45 MeV neutrons, we can use the this expression to show that this detector will measure 100 hits for yields of 6×10^5 DD and 2.6×10^6 DT neutrons.

Since the recoil protons produced by neutron interactions in the scintillator can have any energy from 0 up to the full energy of the neutron, and since the light produced in the scintillator is a non-linear function of proton energy [18], the probability distribution of charge from interacting neutrons is broad. This distribution contributes to the uncertainty in determining the yield from the charge collected from a detector beyond that of Poisson statistics. It can be shown that the statistical uncertainty in the yield increases by a factor [13]

$$\alpha = \sqrt{1 + (\sigma_q / \langle q \rangle)^2} \tag{3.2}$$

where $\langle q \rangle$ is the average charge collected from a detected neutron and σ_q is the standard deviation of the charge. Typically, α is about 1.4, increasing by 2 the number of neutrons needed to achieve a given statistical uncertainty over that predicted by Poisson statistics. Thus, to achieve 10% statistical uncertainty, the nToF-LAND requires yields of approximately 1×10^6 DD or 5×10^6 DT neutrons.

These types of systems are typically not calibrated directly, but are cross-calibrated to absolutely calibrated activation systems. [6,7]

B. Ion temperature

In a reacting plasma, the energy distribution of the neutrons is broadened due to the center-of-mass motion of the reacting ions. For a Maxwellian distribution of ions, the energy distribution of the neutrons is nearly Gaussian. The width of the fusion neutron energy distribution can be measured and the ion temperature of the source region deduced by measuring the width of the neutron pulse arriving at the detector. The width of the energy distribution of the neutron is related to the ion temperature by the equation [19]:

$$\Delta E = \left\{ \begin{array}{l} 82.5 \text{ keV}^{1/2} \\ \\ 177 \text{ keV}^{1/2} \end{array} \right\} \sqrt{kT_i} \left\{ \begin{array}{l} DD \\ \\ DT \end{array} \right. \tag{3.3}$$

where kT_i is the temperature of the reacting ions and ΔE is the full width at half maximum of the neutron energy spectrum. From this, we find

$$\Delta t_{tof} = \left\{ \begin{array}{l} 0.778 \dfrac{\text{ns}}{\text{m keV}^{1/2}} \\ 0.122 \dfrac{\text{ns}}{\text{m keV}^{1/2}} \end{array} \right\} \sqrt{kT_i} \times d \left\{ \begin{array}{l} DD \\ \\ DT \end{array} \right. \tag{3.4}$$

where d is the distance from the source of neutrons to the detector and Δt_{tof} is the full width at half maximum of the neutron time-of-flight signal.

The optimum placement [20] of time-of-flight detectors is determined by a tradeoff between decreased time resolution at small distances from the target and smaller statistical sample of detected neutrons at large distance. Using the relations derived by Lerche [20], one can calculate the uncertainty in ion temperature derived from a neutron time of flight signal. Figure 2 shows that detectors at 6 m and 17 m can give 15% measurements of ion temperature for 10^9 DD and 10^{10} DT neutrons at 1 keV. Better than 10% measurements are possible at higher yields or ion temperatures.

Signals from current-mode detectors can be well described by the convolution of a Gaussian with an exponential decay or sum of decays, [15]

$$h(t; t_o, \sigma, \tau_1, \tau_2) = \sum_i A_i \frac{\exp[-(t - t_o)/\tau_i] \exp(\sigma^2/2\tau_i^2)}{2\tau_i} \times \left\{ 1 + \text{erf} \left[\frac{(t - t_o) - \sigma^2/\tau_i}{\sqrt{2\sigma^2}} \right] \right\} \tag{3.5}$$

The ion temperature can be determined from the value of σ after subtracting the Gaussian part of the response function of the detector in quadrature.

C. Emission time

The neutron emission time is a sensitive indicator of implosion physics, and is therefore a good quantity for comparison of experiment and detailed modeling of implosions.

Neutron emission time t_n relative to a reference point on the laser power history t_l can be determined by using the equation [16]

$$t_n - t_l = \Delta t_{nf} - \Delta t_{lf} + \Delta t_{cal} - \Delta t_{tof} \tag{3.6}$$

where Δt_{nf} is the time between the neutron signal and the fiducial pulse recorded on the neutron detector, Δt_{lf} is the time between the laser signal and the fiducial pulse recorded on a streak camera, Δt_{tof} is the difference between neutron and x ray time-of-flight (calculated from the measured distance of the detector from the center of the chamber), and Δt_{cal} is a calibration constant determined experimentally from the irradiation of a gold disk by a short laser pulse, resulting in a short burst of hard x rays. The x rays are produced at the laser-irradiation time and interact with the detector to produce a signal from which timing information can be obtained. [16]

The detector system is expected to have a response function that is several hundreds of ps wide, but the requirements are for a system that has 100 ps accuracy. In order to accomplish this, a fixed point on the neutron signal must be found and related to the fiducial. A detector, similar to the one proposed here, has been installed on the Omega Laser Facility at the University of Rochester. The signal from that detector (Fig. 3) is well-described by Eq. 3.5 where t_o gives the center of the Gaussian part of the signal and is a good fixed point for comparison to the fiducial.

At the distance proposed for nToF-ET, the time-of-flight spreading of a DD neutron signal for a 3 keV target will be about 800 ps. Together with the detector response, a signal about 1000 ps wide is expected. In order to measure the center of that distribution to 10% accuracy, or the required 100 ps, the signal will need to be made up of at least 100 counts. Using the relations above and the dimensions of this detector, this implies a minimum of 10^7 DD neutrons for an acceptable emission time measurement.

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FIGURES

FIG. 1. Schematic of the nToF-6 and nToF-17 detectors. The nToF-ET detector is similar, but with a smaller scintillator. The fiducial fiber is not shown.

FIG. 2. Evaluation of uncertainty in the analysis of ion temperature from neutron time-of-flight signals for (a) DD neutrons and (b) DT neutrons for detectors nToF-6 and nToF-17 at 1 keV. At higher temperatures, the relative uncertainty decreases at a given yield.

FIG. 3. Fit to the neutron signal from a neutron emission time detector installed on the Omega Laser Facility. The shape of the signal is well described by Eq. 3.5 with exponential decays of 0.55 and 4.5 ns and with $A_1/(A_1 + A_2) = 1/3$.

TABLES

TABLE I. Specifications for each of the detectors in the neutron time-of-flight and emission time system.

Detector	Diameter (cm)	Thickness (cm)	Distance (m)	Main Purpose
nToF-ET	2.5	0.5	0.5	Neutron emission time measurement
nToF-LAND	40	5	6	Low yield measurement
nToF-6	5	0.5	6	Ion temperature for DD experiments
nToF-17	5	0.5	17	Ion temperature for DT experiments

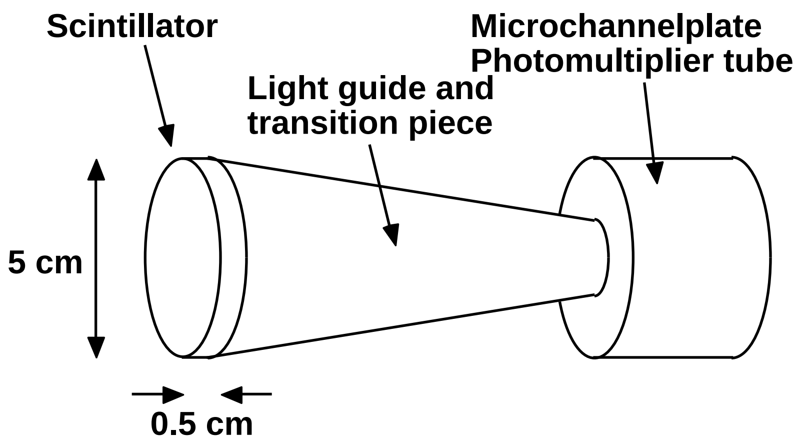
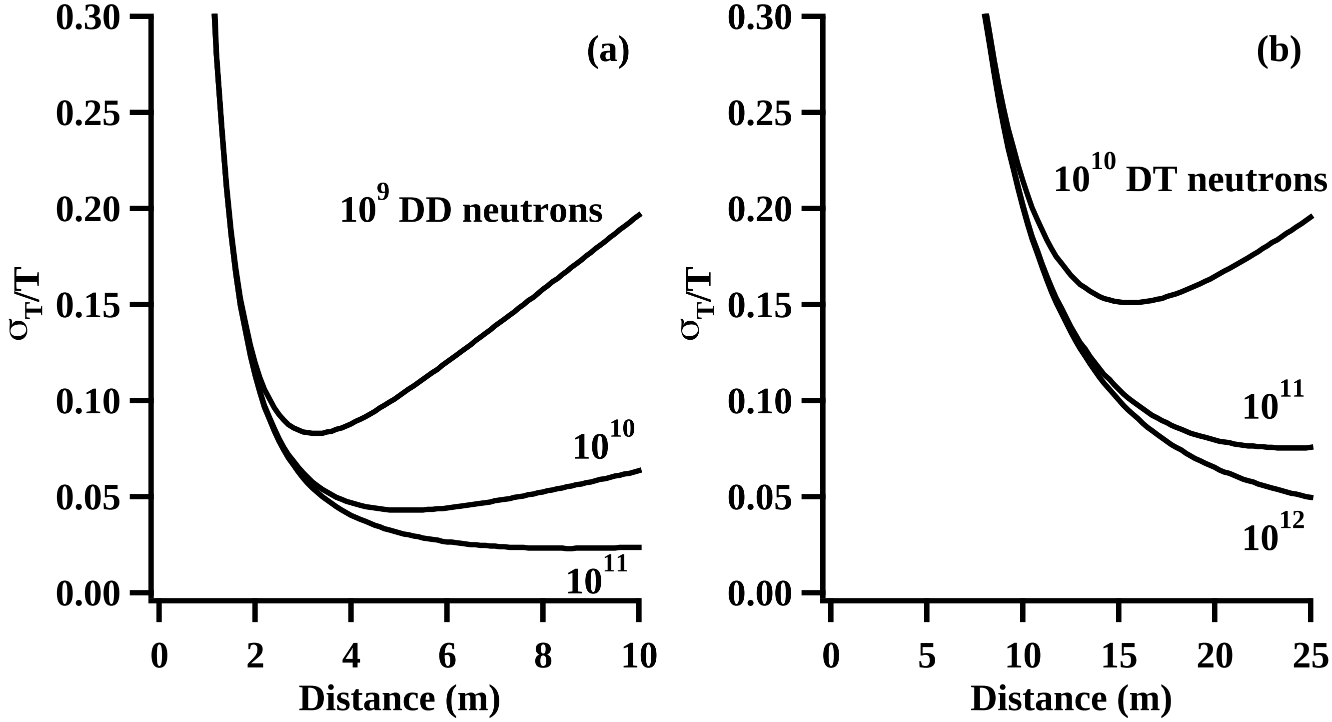

Scintillator
Microchannelplate
Photomultiplier tube
Light guide and
transition piece
5 cm
0.5 cm

Fig. 1



0.30
0.25
0.20
0.15
0.10
0.05
0.00
σ_T/T
(a)
10^9 DD neutrons
10^{10}
10^{11}
0
2
4
6
8
10
Distance (m)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
σ_T/T
(b)
10^{10} DT neutrons
10^{11}
10^{12}
0
5
10
15
20
25
Distance (m)

Fig. 2

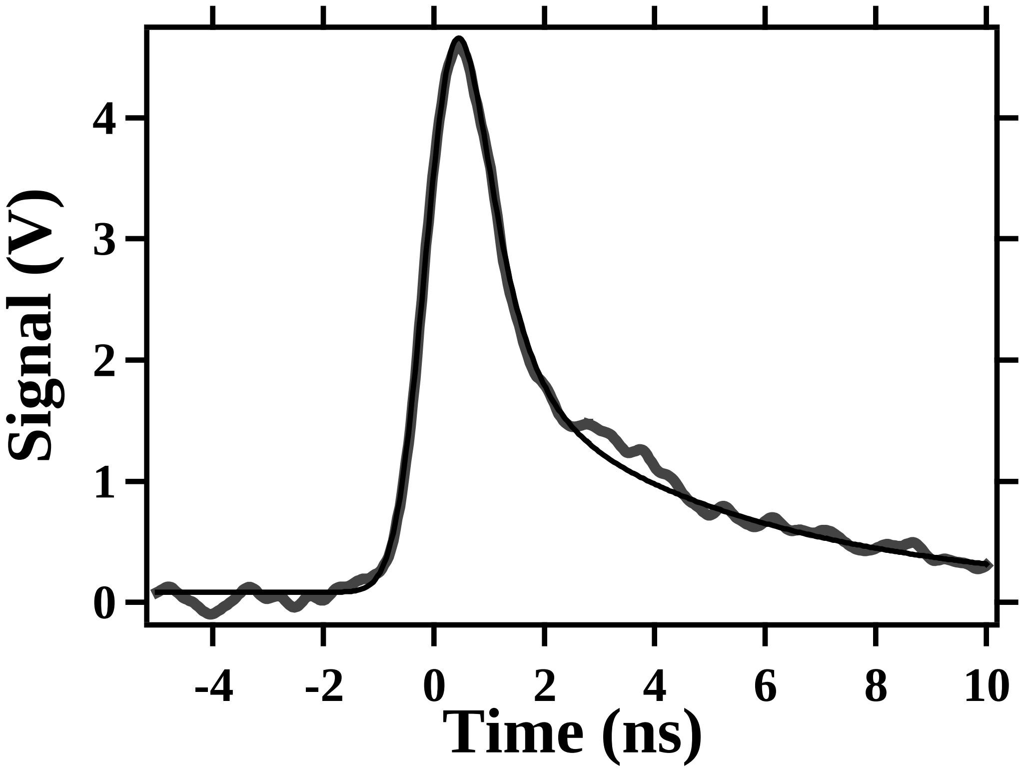


Fig. 3